Above-water radiometry in shallow coastal waters

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Above- and in-water radiometric data were collected from two coastal platforms: a small boat and an oceanographic tower. The above-water data were processed with and without a correction for bidirectional effects (Q02 and S95, respectively). An intercomparison of water-leaving radiances over a wide range of environmental conditions showed (a) total uncertainties across the blue-green domain were to within 4%, (b) a convergence of the Q02 method with the in-water method (average Q02 intercomparisons were to within 4%), and (c) chlorophyll *a* concentrations derived from Q02 reflectances and the OC4V4 (Ocean Color 4 Version 4) algorithm agreed with independent high-performance liquid-chromatography determinations to within approximately 32%. © 2004 Optical Society of America

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1. Introduction

It is commonly recognized that shallow coastal waters are more complex than deep ocean waters in terms of their general composition and optical properties. The emphasis in ocean color remote sensing activities has been on the open ocean because the absorption characteristics are determined almost exclusively by a single constituent: the marine phytoplankton. In this more simplistic, so-called case 1 water type, the measured apparent optical properties can be successfully inverted to estimate the phytoplankton biomass. The latter is usually parameterized by the chlorophyll *a* concentration C_a, which is the dominant phytoplankton pigment. In coastal waters, this inversion process is frequently less accurate because the existence of uncorrelated suspended and dissolved constituents, which produces the so-called case 2 water type, weakens the applicability of a case 1 algorithm.

The global capability to operationally monitor the oceanic biosphere is accomplished through the determination of radiometric quantities—specifically the spectral values of the radiances at the top of the atmosphere, from which (after atmospheric correction) the spectral radiances emerging from the ocean surface $L_W(\lambda)$ are extracted (λ denotes wavelength). Considerable emphasis is placed on the accurate determination of these so-called water-leaving radiances because they are the principal parameters in the inversion algorithms. Indeed, the entire calibration and validation process for a spaceborne sensor is designed to keep the uncertainties in $L_W(\lambda)$ as small as possible. The Sea-Viewing Wide Field-of-View Sensor (SeaWiFS) Project, for example, requires accuracies of 5% absolute and 1% relative in terms of the retrieved $L_W(\lambda)$ values.[1]

Establishing and maintaining the radiometric accuracy of a satellite sensor plus the derived data products involve several continuous calibration and validation activities.[2] Most of these exercises are beyond the scope of the present study, which is restricted to those field measurements suitable for vicarious calibration, as well as the validation or improvement of bio-optical algorithms. Because of the radiometric simplicity associated with the case 1 environment, much of the *in situ* sampling involved is collected in the open ocean far from the tidal mixing, riverine input, and other processes that produce case 2 waters. This emphasis on open-ocean sampling also means that data are collected in rather homogeneous water masses. This has an immediate benefit when the *in situ* sample is matched against the remote sensing observation because it means that small-scale heterogeneity will not add unwanted (and largely artificial) variance to the match-up analysis.

To account for the illumination conditions at the time of the *in situ* sampling, $L_W(\lambda)$ values are usually

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normalized by the global solar irradiance $E_d(0^+, \lambda)$ measured during the sampling interval (the 0^+ symbol indicates a height immediately above the sea surface). This quantity is referred to as the remote sensing reflectance $R_{rs}(\lambda)$ and is the principal parameter used to relate the *in situ* light field to the chlorophyll *a* concentration. Note, however, that the underlying variable that actually describes the optical characteristics of the water mass is the water-leaving radiance.

The two methodologies used to estimate $L_W(\lambda)$ require either in-water or above-water sampling. The former uses vertical profiles of upwelled radiance to establish a near-surface extrapolation interval from which $L_W(\lambda)$ is estimated after propagation through the sea surface; the latter uses direct observations of the radiance emanating from the sea surface, which after correction for glint contamination yields an estimate of $L_W(\lambda)$. There are numerous variations in both approaches, and the in-water methods are distinguished by the vertical resolution of the sampling equipment, whereas above-water methods are differentiated by how glint contamination is removed.

To ensure that the potentially large variety of field measurements were in keeping with the remote sensing accuracy requirements, the SeaWiFS Project convened a workshop to draft the SeaWiFS Ocean Optics Protocols (hereafter referred to as the Protocols). The Protocols initially adhered to the Joint Global Ocean Flux Study sampling procedures[3] and defined the standards for optical measurements to be used in SeaWiFS calibration and validation activities.[4] Over time, the Protocols were revised[5] and then updated on essentially an annual basis.[6–8]

Although above-water determinations of water-leaving radiances are part of the databases used to create global bio-optical models, the majority of the data for these activities are from in-water measurements.[9] Part of this disparity is that in-water measurements have been conducted for a longer time period, and part of it is the consequence of the historically poor agreement between the two methods,[10–13] so traditional in-water measurements have been preferred.

A portion of the discrepancy between the two methods was recently shown to be caused by wave effects,[13,14] platform perturbations,[15] and the anisotropy of the upwelled radiance field[15] (in-water systems are usually nadir viewing, whereas above-water systems are not). The study presented here builds on these accomplishments by analyzing simultaneous above- and in-water optical observations wherein one of the two measurements was unequivocally free of platform perturbations and by implementing an above-water method with corrections for many problems unique to above-water methods. This data set is then used for the following objectives, which are examined within the requirements of calibration and validation activities (i.e., the generalized 1% radiometry needed to satisfy the SeaWiFS absolute uncertainty requirement): (a) evaluate the capabilities of above-water radiometry in shallow coastal waters, (b) determine if the above- and in-water methods converge to within the uncertainties associated with the two methods, and (c) demonstrate the applicability of the above-water observations in bio-optical modeling.

7. Discussion and Conclusions

The uncertainty budgets for the above- and in-water methods across the blue-green domain are to within 4.3% for all the uncertainty sources considered here and to within 3.3% if environmental variability is ignored (Table 2). The total uncertainty budget does not include an uncertainty associated with the different above-water processors. This is not required because the processing of the above-water data does not involve any subjective parameters—each method is processed in exactly the same fashion until the bidirectional correction is applied to the Q02 method. In comparison, the selection of the in-water extrapolation interval is subjective, and the uncertainty associated with that process[39] is a function of the water type and environmental variability. Nearly simultaneous above- and in-water casts were used for the intercomparisons, so it is appropriate to remove some part of the environmental variability and consider 4% as an overall uncertainty for evaluation purposes.

Although individual wavelengths and band ratios in this study exceed a 4% uncertainty threshold, the average spectral intercomparisons for the Q02 (bidirectionally corrected) method are always to within 4% (Tables 3 and 4). The average spectral results for the S95 method, however, always exceed this level, but the band-ratio results for the S95 method always agree with the Q02 band-ratio results to within 4%. These results show that the capability of the Q02 above-water method has converged with the (traditional) in-water method to within the total uncertainties of the measurements and that the band-ratio results from the S95 method are of a comparable quality. Note that this convergence can be considered a verification of the formulation and utility of the *Q*-factor[35,38] to account for the bidirectional properties of the upwelled light field as well as to model the surface reflectance.[17]

Whether the sensors involved are independently calibrated or intercalibrated does not change these basic findings (for the calibration facilities considered here)—in fact, the two types of result agree to within the calibration uncertainty (except one case at 555 nm). The consistency of the independently calibrated results is made stronger by the convergence shown within multiple intercomparison exercises by data produced with independent above- and in-water systems deployed from two different platforms (a ship and a tower) and characterized by different design and intrinsic uncertainties. Furthermore, it is important to remember that both campaign types involved at least one instrument system that was unequivocally devoid of platform perturbations (in one case the in-water system and in the other case the above-water system), and there was no significant difference or bias between the two campaign types or the two instrument types beyond what was identified in the uncertainty analyses. This means that the methodological revisions used with the potentially perturbed data (amplitude filtering, radiometric corrections, sampling thresholds) were sufficient to remove or prevent any contamination artifacts.